Opportunities and Strategies for Testing and Infusion of ISRU in the Evolvable Mars Campaign

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I. Introduction

THE Evolvable Mars Campaign (EMC) is developing the plans and systems needed for a robust, evolutionary strategy to explore cis-lunar space, the Mars sphere of influence (including the moons of Mars), and the surface of Mars. Recently, the emphasis of NASA's plans has changed to focus on the prolonged pioneering of space, rather than focusing on a single crewed mission as the ultimate goal. A sustainable, pioneering vision of space would include in-situ resource utilization (ISRU) in multiple forms and at multiple destinations: atmospheric capture of Mars CO_2 and/or volatiles for consumables and propellants, regolith for bulk and refined materials, and in-situ manufacturing at the Moon, Mars, and other bodies. These resources would enable a reduction in the logistical needs from Earth for future missions, thus preparing the way for a sustained presence on Mars. Although the EMC initially relies only on propellant production for the Mars ascent vehicle via ISRU, one of its primary objectives is to prospect at every EMC destination to understand the potential for ISRU; this will permit true pioneering to be enabled after the first crew arrives at Mars.

Recent and ongoing analysis has considered the possible prospecting measurements that can be performed at the asteroid returned to cis-lunar space by the Asteroid Robotic Redirect Mission (ARRM), at the lunar surface, at Phobos and Deimos, and on the surface of Mars to identify available resources for future use. These opportunities will be available on missions currently in the Evolvable Mars Campaign construct, and will also facilitate the testing and demonstration of resource acquisition, processing, storage, and useage technologies that can play a role in later missions. This analysis has also led to the identification of several objectives that should be targeted during the missions building up to and including the initial crewed missions. These objectives are mapped to strategies for incorporating ISRU to support resource cycle closure and reduce mass requirements from Earth.

This analysis has yielded engineering constraints, based on ISRU, that impact the evaluation of landing sites for missions to the surface of Mars. The terrain of a particular site must be sufficiently flat to permit ISRU systems, as well as ancillary systems such as power and propellant storage tanks, to be landed, moved into position, set up, and operated. Water must be accessible in a form that can be acquired via ISRU, in quantities that align with demands. The chosen method of acquiring and processing water should align with the available resources at a particular site, and that site must have sufficient quantities to meet the requirements (based on crew consumables and propellant demands). Lower altitude landing sites are preferred, as the increase in density can facilitate carbon dioxide acquisition from the atmosphere. Another preference is for sites with a greater ability to move regolith for civil engineering purposes; for example, this would be conducive to both bulk regolith uses (such as the manufacture of berms), and processed regolith uses (such as microwave sintering).

II. Prospecting and Testing Strategy on the Way to Mars

Mars is a deep space destination beyond the Moon where humans can aspire both to survive and to settle. The relative positions of Earth and Mars and associated orbital mechanics make the journey to Mars and back orders of

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magnitude longer than the ones made to the Moon; thus, the technical requirements and constraints, as well as the risks, are orders of magnitude greater. The achievement of a sustained and safe presence of humans on a planet months away of travel from Earth is more likely to succeed if the crew is equipped with the technical ability and know-how to become self-reliant. In pioneering situations on Earth, the knowledge and tools to access local resources and transform them into needed consumables or items has made the difference between a thriving endeavor and its demise. Since other planets are not readily habitable and humans are not physiologically adapted to space environments, this need for self-reliance becomes even more important.

The realization of a sustainable Mars human outpost will not be accomplished solely by the insertion of a few well choreographed tasks focused on exploiting targeted local resources: instead it will be born from the heritage of crews well practiced in the new paradigm of self-reliance in space that result from years of missions during which they developed, tested and relied on the processing and utilization of the resources found in space. Such a well-steeped culture of knowing a planetary environment and possessing the tools and techniques to create survival solutions from the available environment will equip the Martian crews with the creative mindset and psychological assurance that will prove critical for safe long-stays (500 days) on the planet. This culture will be the result of an evolutionary development strategy of ISRU technologies during proving ground missions in cis-lunar space and on the Mars surface that will involve fully autonomous and adaptable robotic machines and crew interaction via teleoperation and direct maintenance or repurposing of hardware.

The deployment of an extensive space resources processing infrastructure to sustain a Mars outpost will be done in phases, each one targeting the emergence of a particular support function or product required by the outpost. The work performed to date by the EMC teams has defined potential concepts of operations in which ISRU is integral for the pioneering of Mars focused on the early emplacement phase of the Mars surface infrastructure. The major roles of ISRU during this phase of pioneering are described below.

ISRU for Ascent Propulsion

The in-situ production of propellants for the Mars Ascent Vehicle (MAV) is the first large benefit of ISRU in the Mars surface architecture. The atmosphere of Mars consists mostly of carbon dioxide (~95.3%), from which oxygen can be extracted for propellant oxidizer. The fuel consists of methane which the EMC currently plans to bring from Earth. Current architecture concepts estimate more than 6 kg of liquid oxygen (LOx) propellant will be needed to lift each 1 kg of the ascent vehicle cabin to a 1-sol Mars orbit; ascent to higher orbits require additional LOx. Since LOx accounts for more than half of the MAV's gross lift-off mass, producing the LOx propellant from in-situ Martian resources provides a significant architectural advantage. The production of LOx at Mars using an ISRU system brought (from Earth) with the MAV and surface power systems sized for producing that LOx, significantly reduces the mass budget of the lander, and positively impacts other transportation systems. Each kilogram of mass saved on the MAV (on the Mars surface) translates into approximately 11 kilograms of mass saved in low Earth orbit. The chemical processes for producing LOx from atmospheric CO_2 are relatively straightforward and the NASA Mars 2020 mission is planning to provide the first demonstration of these necessary technologies on the surface of Mars.

An ISRU system of approximately 1 metric ton (t), using between 25 and 40 kWe of power, can produce the LOx required for the MAV prior to the arrival of the crew in the Mars sphere of influence. The range of power needs depends on both the total LOx requirement, and the time available to operate the system. This power requirement drives the sizing of the surface power system, which consists of several modular "kilopower" (kP) units each capable of producing 10 kWe. These kP power systems also provide power for the other surface systems, primarily the crew habitat, after LOx production is complete. Additionally, the size of the MAV with imported methane (CH_4) but without Lox, impacts the required payload capability of the Mars lander which delivers it. Thus, the use of ISRU has critical impacts on other elements of the architecture.

Once ascent LOx propellant production is completed, the ISRU plant is available to make oxygen for other uses, assuming power can be shared with the habitat and other surface systems. Subsequent missions to the same landing site can reuse the power systems, thus reducing the landed mass needed for later visits to the initial location.

Recent robotic Mars missions have established that water is widely distributed in the Mars regolith with some local concentrations. Hydrocarbon ascent fuel (e.g. CH_4) can be produced using Martian resources by processing water and/or hydrogen extracted from water-bearing regolith (ice, hydrated minerals) with atmospheric CO_2. Early work currently under way by the ISRU & Civil Engineering Working Group (ICE WG) and other science-focused working groups for the Human Landing Site Study (HLS^2) Steering Committee on the selection of a Mars landing site for

exploration by human crews, indicates that access to significant quantities of water is an important criterion for site selection. The operational concepts for water extraction from Martian regolith are being developed based on models of water distribution taking into account the current uncertainty in the distribution of water on Mars. The ICE WG will provide recommendations for the collection of data needed from Mars orbital assets (MRO and future robotic spacecraft) to reduce the uncertainties on the nature and distribution of water usable for ISRU. The use of pathfinder robotic missions on the surface of Mars is also under definition to yield new scientific findings about surface composition and possible demonstration of regolith processing operations and hardware.

ISRU for Mars Site Infrastructure Growth

The emplacement phase of the first elements of the infrastructure will aim at providing the first crew with their most important needs: a habitat with adequate environmental protection and a life support system, electrical power, communication capability, EVA and surface transportation capability, a fueled MAV for return to Mars orbit.

Robotic ISRU regolith excavation and handling assets can play an important early role during this phase beyond the search, acquisition and processing of water for the MAV. Because the placement of the different elements follows guidelines on distances from surface fission power reactors and from landing zones to avoid both radiation and landing plume ejecta, the robotic regolith-handling elements can become versatile workers to accomplish many tasks. Working as a coordinated group (swarm), they can perform a precise terrain survey prior for the landing of heavy landers and prior to the emplacement of habitat modules. As needed, the ISRU excavators and haulers could prepare the sites and consolidate foundations for landing pads and habitats. They could also erect berms with regolith to protect elements that require it and to possibly reduce the long spacing requirements between landing zones and other surface site elements. Other alternatives include using natural features in the Mars landscape such as stable bedrock and hills to provide shielding and protect other surface assets.

The crew can also begin to leverage other resources available on the Martian surface to further reduce the material needing to be brought from Earth. Their work with surface robotic assets will reveal new sources and ways to access water and identify the challenges and solutions to process it. In later missions and into the Consolidation phase, at certain locations and with sufficient power, copious amounts of water may be harvested, reducing consumables brought from Earth for the crew and facilitating industrial processes with chemistry that yields fuels and plastics. These same resources may also be used to produce food on a large scale. As additive manufacturing and related technologies mature on Earth, they may be deployed on Mars to provide replacement parts, structures, and shelters to expand living and working space.

EVOLUTIONARY ISRU TECHNOLOGY DEVELOPMENT

The gradual insertion of ISRU technologies and concepts of operations into the critical path of deep space missions should follow a systematic progression of capabilities demonstrated through increasingly challenging environments. NASA's EMC enables this type of technological evolution for the first time by using ground test facilities, current in-space assets such as the International Space Station (ISS), planned asteroid and lunar science missions, and pathfinder missions in LDRO and at Mars in the coming decades. Early ISRU prospecting and processing tests on a carbonaceous C-type asteroid at LDRO could lay the groundwork for harvesting resources from the Mars moon Phobos that appears to have similar characteristics.

Prospecting for resources. Understanding what resources exist, their form, concentration, and distribution is essential to harvesting and utilizing these resources in future missions. Development of the technologies needed for asteroid resource prospecting will leverage both the Curiosity rover Sample Analysis on Mars (SAM) instrument (Leshin, 2013) and the Regolith and Environment Science & Oxygen and Lunar Volatile Extraction (RESOLVE) instrument under development for the NASA Resource Prospector (RP) mission (Sanders, 2012). In both instruments, small soil/regolith samples are extracted using a drill and heated in an oven; the released volatile gases are analyzed with a gas chromatograph/mass spectrometer. Modifying these processes for operation in microgravity will require work described in the following subsections.

Ground Testing and Microgravity Testing. Extensive ground testing of sub-scale to near-full scale ISRU hardware has been taking place at NASA facilities, universities, companies, and international institutions. The number of facilities that can create relevant environments (beds of regolith and high-fidelity resource simulants such as ice and volatiles under vacuum, thermal environment) is very limited and require more investments to accommodate the needs of prototype hardware and their functions. Terrestrial analog testing provides valuable data on issues such as repeated handling of regolith, end-to-end coordinated processes, and tele-operation practices (Larson, 2011). This

ground development process must continue unabated and technologies must transition as soon as possible to a microgravity environment where complex issues that cannot be simulated well on the ground should be tackled. The ISS is currently projected to continue operations possibly until 2024 and provides an ideal platform for extended testing of ISRU technology in preparation for space mission use. The absence of significant gravity during operations at an asteroid changes not only the nature and behavior of the regolith and the bound resources but also the excavation, handling, and transporting of such material during which reaction forces and momentum conservation are dominant. Similarly, the processing of regolith and resources in reactors where gases, liquids, and solids mix and interact is affected in multiple ways by the microgravity environment. Such ISRU technologies would be relevant to asteroids, Phobos and Deimos environments.

Exploration Augmentation Module. While the ISS currently offers a variety of experiment racks and supporting capabilities to perform self-contained ISRU processes on a small-scale, the addition of an external carrier platform capability would allow an extensive technology maturation program for ISRU technologies on all processes and at the proper scale. An Exploration Augmentation Module (EAM) is under consideration and the EMC could accommodate ISRU activities as well as other systems with similar needs for technology maturation. Some ISRU processes, such as the conversion of trash to propellant reagents or consumables, can be performed inside a habitat with crew present. In addition, the 'dirty' and hazardous nature of space resource processing activities and the scale of end-to-end processes (from regolith acquisition to delivery and storage of the targeted resources) will often require that they be conducted outside crew modules and exposed to the space environment. ISRU hardware designed to access, acquire, transport, and process asteroid regolith would undergo testing and validation on an external rack or platform where the combination of microgravity, vacuum, and thermal constraints affects each process and the processed materials. The "open-to-space" capability would also be able to accommodate larger subsystems undergoing scaling tests.

Asteroid Retrieval Crew Mission (ARCM) and asteroid ISRU in cis-lunar space. In the next phase, ISRU technologies would follow their evolutionary path toward deep space implementation when an EAM could be brought to the lunar orbit where the captured asteroid will be residing at the completion of the ARRM mission. As previously described, significant data on the resources of the asteroid could have been gathered and analyzed during the ARRM mission to inform what type of ISRU technologies are best suited to work with the available asteroid. A variety of concepts of operations are under consideration for ISRU activities with the redirected asteroid.

- ISRU assets installed externally to the EAM can be tele-operated by the astronauts during one of the ARCM missions, including surface rovers, landers or surface equipment emplaced by robotic arms for prospecting and sampling. The material can then be brought to reactors on the EAM external ISRU processing platform for resource extraction, analysis, storage and conditioning.
- In more matured versions, autonomous equipment can perform some activities such as continued prospecting, new operations practices, and long-duration systems testing in deep space while the crew is absent. Tele-operations from Earth are also possible during that stage to maximize the testing time and to advance knowledge of systems behaviors during long exposure in space.
- The selection of the asteroid for the ARRM mission will play a defining role in what type of ISRU can be demonstrated and validated for future implementation in Mars missions. The selection of a volatile-rich carbonaceous C-type would enable the prospecting and extraction of water (~ 10-20 wt.% estimated), and perhaps processing the asteroidal material into in-space fabricated radiation shielding panels that can protect deep space habitats and/or spacecraft on their way to Mars.

ISRU for Mars Transit and Phobos missions. The technology maturation program will culminate in the flight qualification of ISRU hardware specifically selected for use on missions to the Mars system. The deep space habitat that will carry a crew during its long transit to Mars destinations such as Phobos, Mars orbit or the Mars surface would benefit from advanced technologies converting on board trash into propellant (methane, oxygen) or consumables (breathing oxygen, water), and extracted asteroidal material into radiation shielding. The possible visit of a crew to Phobos could make a direct use of the propellant made during transit as a way to keep a station orbit near the Mars moon and the synergistic use of ISRU technologies on a C-type asteroid at a lunar distant retrograde orbit (LDRO) could directly apply to resource extraction at Phobos on similar materials.

Mars Pathfinder missions and Mars Surface missions. The use of atmospheric CO_2 capture and processing technologies onboard the Mars 2020 rover is an important step taken by NASA toward validating ISRU technologies with potential for large-scale implementation in Mars surface human missions. The concept of processing the Martian

atmosphere (containing over 95% carbon dioxide) to extract oxygen for the propulsion of a crew ascent vehicle for a return to Earth has been studied extensively and is under consideration for the EMC. The production and storage of oxygen would need to be done autonomously by ISRU surface assets ahead of the arrival of a crew. A similar concept would see the extraction of water (H_2O or OH) from the regolith and its conversion into oxygen and hydrogen, the latter being then used in a Sabatier reaction with carbon dioxide for the production of methane as the fuel for the crew Mars ascent stage rocket engine.

The development path for ISRU technologies within the Mars campaign will culminate in these critical applications and others like the use of extracted water for life support or additional exploration capabilities, the on-site construction of landing areas by consolidation of regolith, the creation of habitat protection against radiation, and the protection of other arriving spacecraft from landing debris. as well as in-situ manufacturing from in-situ derived feedstocks.

Public-Private Partnerships and Commercial ISRU at Asteroids. Governments are not the only interested partners in the development of technologies for the utilization of space resources. The inclusion of asteroid missions in the EMC invites a strong synergy between private and government interests to combine efforts and maximize the use of data and techniques. The presence of a captured asteroid with valuable resources in a stable lunar orbit may prove attractive for companies aiming to mine such objects. The development of ISRU technologies in the proving ground years can be done with shared financial commitments and contractual arrangements that benefit every partner. The Mars-forward momentum will likely carry the public interests away from the captured asteroid that could in turn become a prime mining location for private entities. The legacy of the captured asteroid becoming the source of accessible space resources could in time be the ignition spark of an emerging, new space-based economy.

III. Landing Site and Engineering Constraints for Mars Surface ISRU

The largest mass landed on Mars to date has been the Mars Science Laboratory (MSL) rover named “Curiosity”. The mass of Curiosity is 899 kg and required the most sophisticated entry, descent and landing system (EDL) for Mars that has ever been built, with a “sky crane’ performing the final deceleration maneuver. Current EMC studies are considering much larger landed masses on Mars ranging from 18,000 to 27,000 kg. This represents a large order of magnitude increase in the EDL system capability and implies that new methods for all three phases of EDL must be developed. The landing is particularly challenging, if a rocket engine is used to decelerate the lander, since the plume will interact with the regolith on the Mars surface to create fluidization and deep cratering of the soil under the lander, and ejection of gravel and rocks from the crater. On Mars the larger thrust and weaker soil cause the soil to fluidize and shear creating a deep hole, whereas on the Moon’s vacuum, the behavior is different resulting in just erosion and surface scour. On Mars in the thin atmosphere the gravel flies the farthest, whereas on the Moon in vacuum the dust goes the farthest. As a result, the gravel or rocks will be accelerated and ejected away from the lander up to 1,000 meters from the landing site (Metzger et al. XXXX). In fact, during the MSL sky crane landing sequence some debris was ejected from the surface creating a shallow crater before exposing bedrock, and pebbles were found on the deck of Curiosity and one sensor was damaged. (Reference required).
Solutions involving ISRU include building landing pads and berms to mitigate the effect of the rocket plume impingement. Other natural solutions may exist by using areas with bedrock and terrain features which could shield the other Mars station assets from ejecta damage. Landing sites altitude will also be dictated by the EDL system capabilities. Lower altitudes are preferable, because the EDL system has more time in which to be effective prior to lander vehicle touch down. The chosen landing site should be relatively flat – during the Apollo missions the ascent stage was constrained to being within 12 degrees of level for a successful launch back to Earth (reference needed) . Large rocks and boulders could cause damage to the landing gear or the lander itself, or they could cause tipping of the lander at touch down, so large flat, rock and boulder free terrain is desired. Natural impact craters are also hazards that need to be considered and avoided, unless they are so large that they can be used as a landing site themselves. Other considerations are that civil engineering construction (pads, berms, shelters, habitats, roads, shielding) require bulk regolith as a raw material. Loose and easily obtainable regolith is preferable for construction material for emplacement as loose granular material or as a concrete type of structural material.

IV. Mars Water Production for ISRU

Based on the current climate conditions on Mars, water vapor is an extremely scarce resource in the Martian atmosphere. If the Martian atmosphere could be collected inside a column that extended upward from the surface towards space and the amount of water contained in the column was condensed, then the thickness of the water layer would only be 10 micrometers (Read and Lewis, 2004). Based upon that estimate, the maximum mass of water that would condense on average over a surface area of one square meter would only be one gram.

However, water is expected to exist in much higher concentrations on Mars in the form of hydrated minerals and as solid ice at the polar ice caps. Water ice has even been detected in the mid-latitudes. Subsurface glaciers composed of water ice were detected in the central latitudes using the shallow radar system (SHARAD) onboard the Mars Reconnaissance Orbiter (Holt et al., 2008). More recent ice flow modeling (Karlsson et al., 2015) has shown that a global ice coverage of 1.1 meter depth may exist on Mars, implying that water ice may be hidden under the regolith in the mid-latitudes in amounts that could satisfy the propellant needs of a MAV when ISRU technologies are used to produce all of the propellant.

If water ice is not readily accessible at a particular landing site on Mars, then hydrated minerals must be prospected, excavated and processed to extract the needed water. The water that is bound in the form of hydrated minerals requires thermal energy to release the water molecules by desorption. However, there is a maximum temperature that hydrated minerals can be heated without also releasing contaminants, such as perchlorates, which means that extracted water will need to be purified.

ISRU will play a key role in enabling space pioneering on Mars by utilizing planetary resources to make consumables that do not need to be transported at great expense out of the Earth's gravity well. Water is a critical resource that directly provides life support for humans and plants, and indirectly can provide oxygen both for life support and for propulsion. When water is electrolyzed into oxygen and hydrogen, the oxygen can be liquefied for storage (LOX) and the hydrogen can be chemically reacted with carbon dioxide collected from the Martian atmosphere to form methane (CH4) that can also be liquefied (LCH4). The chemical conversion process for methane production can be represented by the following simplified molecular reaction formula

$$2\ H_2O + CO_2 \rightarrow 2\ O_2 + CH_4.$$

In terms of molecular mass (in grams per mole), the water molecule is 18.015 g/mol, carbon dioxide is 44.010 g/mol, the oxygen molecule is 31.999 g/mol, and methane is 16.042 g/mol.

Hence, in order to produce 1 kg of methane and 3.989 kg of oxygen molecules, it would take 2.246 kg of water, 2.743 kg of carbon dioxide. Assuming that the MAV's propulsion system is based on a LOX/LCH4 ratio of 4:1, then a LOX requirement for 25,000 kg will also require 6250 kg of LCH4, which means that 14,040 kg of water and 17,140 kg of carbon dioxide would need to be extracted from the regolith and collected from the atmosphere, respectively. In terms of hydrated minerals in the regolith, if the water concentration in the regolith is 5% by weight, then 281 metric tonnes of regolith would need to be processed to supply the LOX and LCH4 propellant for one MAV.

Core drilling is an excavation technique that has been combined with heating of the regolith to liberate water from regolith (hydrated minerals or mixtures of ice and regolith) as a vapor and then condensing the water vapor in a storage tank (Zacny et al., 2012). Drilling into pure ice or icy regolith tends to produce ice cuttings that behave like dry regolith provided that the water remains frozen. Percussive drilling (as opposed to static drilling) combines rotation with hammering, which chips and breaks up the icy regolith. The main disadvantage of percussive drilling is that it requires more power than non-percussive drilling due to the additional powered actuator needed to drive the percussive mechanism. However, the percussive drill penetrates icy regolith faster and much more efficiently than a rotary drill.

Excavating rovers (excavators) have also been developed to remove the overburden of dry regolith, and then collect and transport hydrated mineral regolith or mixtures of ice and regolith to a water-regolith processor where the water is extracted by drying the hydrated minerals. After the water has been collected and filtered, it is electrolyzed and stored as LOX and the spent regolith can be utilized for civil engineering by constructing berms, or for additive manufacture of parts. Small excavators, such as the current prototype version of the Regolith Advanced Surface Systems Operations Robot (RASSOR 2.0), (Mueller et al., 2013) being developed at KSC, can collect 80 kg of

regolith per trip in only a few minutes, and can operate for 16 hours before requiring its batteries to be recharged. Continuous excavation can be accomplished using three small excavators in which one excavator is being recharged at any given time. Two continuously operating small excavators could excavate the required 281 mT of regolith in about 1760 round trips. Assuming 16 round trips per excavator per day (i.e., one trip per hour), it would take two continuously operating small class excavators about 110 days to excavate the 281 mT of regolith. Given this rate of excavation for a team of three small class excavators, the water-regolith processing system is likely to be the limiting factor in determining the production rates of LOX and LCH4.

V. Conclusion

Recent studies suggest that water, oxygen, and metal resources on the Moon, NEA's, and Mars are critical for achieving NASA's long-term goal of Earth Independence for human deep space missions to continue the exploration of our solar system as well as begin the establishment of commercial transportation and construction in space *(Insert references).* The NASA Resource Prospector (RP) mission is likely to find water ice and other volatiles at the Moon's poles. When it does, the next logical questions involve, how to mine and extract the resources, and how this will benefit future exploration of the Moon and beyond. NASA is also considering redirecting a Near Earth Asteroid (NEA) to cis-lunar space. Following the in-situ scientific study of this NEA to understand the history and development of our solar system, the opportunity to test resource extraction methods and technologies on this body arises logically to advance sustainable human exploration and economic development in space. The development of lunar and NEA regolith resource extraction methodologies and technology portfolio is part of the Evolvable Mars Campaign (EMC) Proving Ground to create a new enabling capability for future Mars missions (Bobskill et al., 2015). Hardware designed and proven in microgravity and deep vacuum will enable the resource prospecting and extraction activities on Martian moons Phobos and Deimos to support the cis-Mars transportation infrastructure currently envisioned. Mars regolith processing logically benefits from such leveraged development to achieve ultimately the acquisition and extraction of water and hydrates held in the regolith to further the self-reliance of a Mars human outpost.

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References

1. Holt, J.W., et al. (2008). "Radar sounding evidence for buried glaciers in the southern mid-latitudes of Mars," Science, 322, 1235-1238.
2. Karlsson, N. B., et al., (2015). "Volume of Martian midlatitude glaciers from radar observations and ice flow modeling," Geophys. Res. Lett., 42, 2627–2633.
3. Linne, D. L., Sanders, G. B., and Taminger, K. M. (2015). "Capability and Technology Performance Goals for the Next Step in Affordable Human Exploration of Space," presented at the 8th Symposium on Space Resource Utilization - AIAA SciTech, Paper #2015-1650, 5-9 January 2015, Kissimmee, Florida.
4. Mueller, R. P., et al., (2013). "Regolith Advanced Surface Systems Operations Robot Excavator (RASSOR)," NASA Tech Briefs, Article 15471, January.
5. Read, P. L. and Lewis, S. R., (2004). "The Martian Climate Revisited," Springer-Verlag Berlin Heidelberg.
6. Zacny, K., et al., (2012). "Mobile In-Situ Water Extractor (MISWE) for Mars, Moon, and Asteroids In-Situ Resource Utilization," presented at the AIAA SPACE 2012 Conf. – Paper #2012-5168, 11-13 Sept. 2012, Pasadena, California.